Considerations for the SNS Ring BLM System Design

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Since the SNS will be a very high average power machine, activation from the uncontrolled beam loss must be kept to a level which would allow safe machine maintenance. To achieve this the CDR specifies a loss of 1 part in 10^4 of the full Ring intensity, which is $2x10^{10}$ per cycle, for a 2 MegaWatt beam. This could occur in a variety of ways. For example,

1. The full $2x10^{10}$ loss occurs over the first few turns. This might happen if the beam at injection is grossly off energy or the ring dipole currents are incorrectly set. If the Linac energy is off design the beam would be unable to negotiate the arc in HEBT and would be lost there, unless the HEBT dipoles were set for the same off design momentum. It is also possible for the Ring dipole current to be set improperly, causing the full injected beam to be lost in the Ring.

2. There is a problem with injection causing a fixed percentage of the injected beam to be lost. This will result in a constant fraction of the injected beam being lost so that the loss is uniform over time. This is a likely scenario.

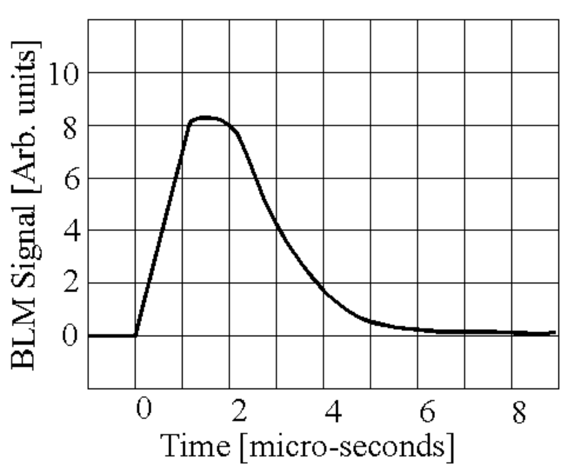
3. There is a loss proportional to the circulating beam in the Ring, which will then increase linearly with time. Losses of this type are to be expected.

4. There is a loss which grows non-linearly with intensity, due to space charge blow up or an instability, resulting in a rapid loss of significant beam over tens to hundreds of revolutions. While instabilities are not expected in the SNS Ring, space charge may lead to halo generation.

These losses can, of course, occur in combination.

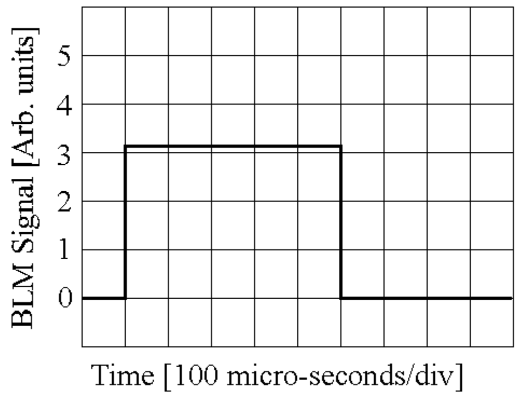
<u>CASE 1. Full Loss of Injected Beam.</u>

To accumulate $2x10^{14}$ protons over 1168 turns will require $1.73x10^{11}$ protons to be injected per turn which is equivalent to a current of 32.9 mA averaged over the 0.975 msec the cycle. This full current can be lost if the Ring dipole current does not match the injected momentum and the criterion of 10^{-4} loss will be reached in a less than 1 turn. If the momentum error is large then the beam will hit in one spot. This can occur if the Ring dipole current is set in error. If the Linac beam is far from the design momentum it would be lost in the HEBT arc to the Ring. For a small Ring dipole current or Linac momentum error, the beam will hit at the center quad in each of the four Ring arcs, which are points of maximum dispersion. A transient error in Linac momentum could occur if the beam loading compensation is not functioning properly. In this case the beam at the beginning of the cycle is likely to be off momentum and will be lost. This is illustrated in Figure 1.



CASE 2. Loss of Fixed Fraction of Injected Beam.

The injected beam passes through the stripping foil which converts it from H-minus to protons. Most losses resulting from this will be handled as “Controlled” losses, that is, at components designed to tolerate these losses and not activate Ring components. However, some losses may occur from mis-match or excessive halo in the injected beam and will not occur at the “Controlled” loss dumps. This will appear as a constant loss throughout the cycle since it only depends on the injected turn and not the circulating beam. If this fraction of the injected beam is too high, the accumulated loss over the cycle may reach the 10^{-4} level even though the amount of current lost is small. In this case, 10^{-4} of the injected beam is 3.3 μA, lost continually over the entire 0.975 msec duration of the cycle. This is shown in Figure 2 below.



CASE 3. Loss of Fixed Fraction of Circulating Beam.

As the beam is accumulated in the Ring a portion of it makes repeated passes through the stripping foil, leading to emittance growth and momentum change for those particles. These may later be lost around the Ring. Orbit or envelope errors may also lead to scraping of the tails of the circulating beam. If the circulating beam is $I_C(t)$, the loss current is $I_L(t)$ and the loss fraction k , such that $I_L(t) = k\, I_C(t)$, then :

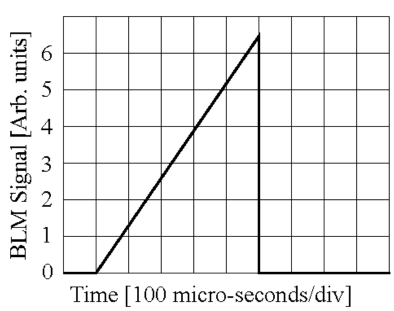
$$I_L(t) = 2\, k\, Q_T\, (t/T^2)$$

Where Q_T = the total charge in the machine at the end of the cycle and T is the total accumulation period. For:

$$Q_T = 2 \times 10^{14}$$
$$k = 10^{-4}$$
$$T = 0.975 \times 10^{-3} \text{ seconds}$$

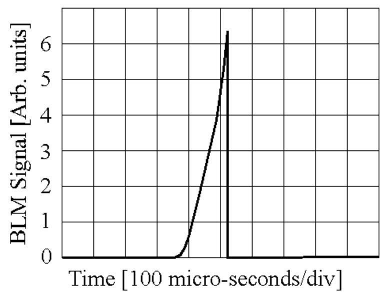
$$I_L(t) = 6.73 \times 10^{-3}\, t \quad [A]$$

And at the end of the cycle, $I_L(t)$ = 6.56 μA., which, as expected, is twice the average loss current of case 2. This is shown in Figure 3 below.



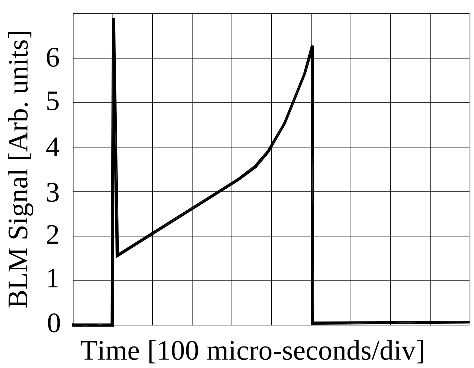
CASE 4. Non-Linear Loss due to Circulating Beam.

As the beam accumulates in the Ring the collective forces increase. This depends non-linearly on the intensity in the Ring and may lead to halo generation and subsequent scraping on limiting apertures. Instabilities are not expected to be a problem in the Ring but simulations continue. Figure 4 shows what such a loss would look like.



CASE 5. Combinations of Above Losses

Clearly all of the above cases can occur in a single cycle. This is shown schematically in Figure 5a and in an actual scope trace taken at the PSR (courtesy of M. Plum of LANL and J. Galambos of ORNL) in



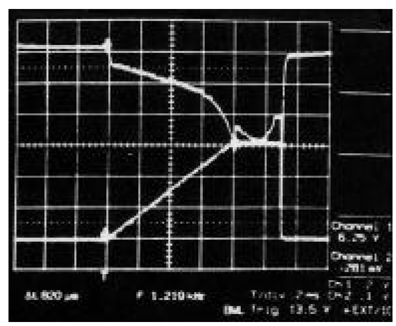


Figure 5b. The schematic version shows an injection momentum loss not present in the actual PSR losses, but, aside from being inverted, it looks very much like the actual loss.

The four cases give current loss ranging from 32.9 mA due to losing the full first turn of beam, to 3.3 micro-Amps from uniform beam loss over the entire cycle. The Linac section of the CDR states that a loss of 1 nA/meter would not lead to excessive activation. This number represents the current lost over 1 second (60 pulses), and not the peak current lost during the beam-on time. For comparison let us take the case of uniform Ring beam loss (3.3 μA during the beam on time of 0.975 msec) and divide by the 220 meter circumference of the Ring giving 15 nA/meter. The difference between this and the Linac's 1 nA/meter, is the beam duty factor, as previously explained. However, this number is misleading since it is not likely that the beam would be lost equally "per meter" but would hit at the maxima of the beta functions in the Ring. Disregarding the collimators, these occur at the quadrupoles, which is where the majority of the BLMs will be located. It is reasonable to talk in terms of the loss per BLM, which would be given by the dividing the total loss by 48, the number of quads in the lattice for a value of 68.8 nA/BLM.

Correlating Current loss and Expected Signal Level.

The Linac section of the SNS CDR (page 3-97) claims that a loss of 1 nA/m at 1 GeV corresponds to 115 rad/hr at 28 cm from the beam center line. There is no explanation of this number and no reference so it is not clear what criteria were used or if it applies to the accelerating cavity region of the Linac or the much more open HEBT transfer line. However, let us take the LANL conversion of 1 nA/m to 115 rad/hr and scale it from 28 cm to 10 cm, the actual beam pipe radius in the Ring. This gives a value of 902 rad/hr. If we consider Case 3, a fixed fraction loss of the circulating beam, then at mid-cycle this gives a dose rate of 6.2×10^4 rad/hr or 17.2 rad/sec. The ion chamber sensitivity is nominally 70 nC/rad. Since we will only be observing the electrons, the conversion will be half this value, resulting in an average signal current of 603 nA. The noise equivalent current observed in the AGS-to-RHIC (AtR) transfer line, and the RHIC Sextant test was 10 pA, so even first turn losses should be easily observed. These estimates are based on the LANL CDR conversion figure of beam loss to activation level. This number needs to be verified.

Signal Processing Considerations.

The Ring loss criterion is that the sum of losses in the cycle be below 10^{-4} of the total circulating beam. For tuning purposes, a display of current can directly show when in the cycle losses occur and the character of those losses, but for Beam Protect purposes the integrated loss signal is the proper data. The current could be integrated electronically or amplified and summed digitally to give the accumulated loss in the cycle. The 10^4 dynamic range in current (single point loss over one turn versus low level loss over the full cycle around the full Ring) presents a difficulty for a simple amplifier. A similar problem existed for the RHIC BLM System which was required to protect the superconducting magnets against quenching due to large single turn losses and low level slow losses. This was solved by shunting the amplifier input with a pre-integrating capacitor to “soak up” any fast loss spike. In RHIC the capacitance and input resistor were chosen to simulate the thermal time constant of the superconducting magnet, which does not apply here. For SNS, however, the charge on the capacitor must be removed at the end of each cycle. Even with this pre-integration the large dynamic range will probably still require gain to be switched at least once during the cycle.

Two components contribute to the loss monitor signal: current due to the electron motion and due to the ion motion. Typically the electron collection time is a few microseconds or less while the ion collection times run from 1-3 milliseconds. The signal estimates here were based on only the electron current, assuming that the slower ion current would not contribute during the cycle. However some of the ions are created near the collection electrode and will be part of the signal. While this should represent a small portion of the total signal, a more careful estimate should be made including their contribution.

Another consideration is that the 10^{-4} loss figure is for the entire Ring, not just a single point. Thus, the sum of the outputs of all detectors (at least those at the quads) must be used to determine if the loss for the cycle is tolerable. Since the electronics for all detectors in the Ring will be located in a common rack it would not be difficult to perform this summation. One interesting implementation of the circuitry would be to amplify or integrate the signal from the detector and immediately convert it to digital form on a turn-by-turn basis. This would provide over-sampling to avoid aliasing. The results could used for a loss display and conveniently summed using a DSP or micro-controller or other dedicated processor to obtain the total loss. A digital comparator would then perform the beam loss criterion monitoring.

Conclusions

The criteria for acceptable un-controlled loss in the Ring should be further discussed and a common definition agreed upon. For example, “loss per meter” may not be as meaningful as “loss per BLM or quad. An accepted conversion factor for 1 GeV proton beam loss to activation level must be established.

The expected signal levels are well within the range of the proposed detectors. An integrated signal summed over all detectors (those at quads only) is required to determine if the losses exceed 10^{-4} of the final beam. Care must be taken in the electronics design to allow for high level losses over a few turns as well as low level losses over the entire cycle.